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Discovery of X-ray emission from the proto-stellar jet L1551 IRS5 (HH 154)

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Abstract. We have for the first time detected X-ray emission associated with a proto-stellar jet, on the jet emanating from L1551 IRS5. The IRS5 proto-star is hidden beyond a very large absorbing column density, making the direct observation of the jet's emission possible. The observed X-ray emission is likely associated with the shock "working surface", i.e. the interface between the jet and the circumstellar medium. The X-ray luminosity emanating from the jet is moderate, at $L_{\rm X} \simeq 3 \times 10^{29}$ erg $\rm s^{-1}$, a significant fraction of the luminosity normally associated with the coronal emission from young stars. The spectrum of the X-ray emission is compatible with thermal emission from a hot plasma, with $T \simeq 0.5$ MK, fully compatible with the temperature expected (on the basis of the jet's velocity) for the shock front produced by the jet hitting the circumstellar medium.

1. Introduction

During the final stages of the formation of low-mass stars (in the so-called classical T Tau phase) accretion of material from the proto-stellar nebula onto the Young Stellar Object (YSO) takes place through an accretion disk. Very often the presence of the accretion disk is correlated with the presence of energetic polar outflows, that is, collimated jets of material being ejected perpendicularly to the disk, along its axis. When these jets collide with the surrounding ambient medium – or with previously ejected material – they form a shock structure, which is directly observable in the form of so-called Herbig-Haro jets.

X-ray emission (and thus the presence of hot plasma, at temperatures in excess of several $\times 10^5 K$, up to $\simeq 100$ MK during energetic flares) has by now been observed in most stages of the formation of low-mass stars, ranging from the highly embedded, perhaps spherically accreting proto-stars (Class 0 objects)

to the final stages of the pre-main sequence life of a star, the Weak-Line T Tau stage, during which the X-ray luminosity is thought to come from a "normal" (however very active) stellar corona (e.g. Feigelson & Montmerle 1999).

While accretion itself has been considered as a possible source of X-ray emission in classical T Tau stars, up to now no evidence of energetic phenomena associated with proto-stellar jets has been observed. Here we present the first observations of X-ray emission from a proto-stellar jet, obtained in a well-studied system in which the proto-star (and its immediate circumstellar environment) powering the outflow is so heavily obscured that the jet can be singled out as the source of emission of the X-rays without ambiguity. Our observations show that this jet is indeed an X-ray source with a luminosity equivalent to a significant fraction of the X-ray luminosity normally associated with YSOs. The observed X-ray spectrum is compatible with a thermal origin of the observed X-ray emission. The associated temperature is moderate, well matched to the shock velocities observed in this and other Herbig-Haro jets. This raises the question of whether the X-ray emission associated with jets could indeed be a common feature of stellar formation, so that in some cases a significant fraction of the X-ray luminosity associated with the star (YSO/accretion disk) is actually emanating from shocks in the jet.

2. The L1551 IRS5 outflow

The L1551 cloud is one of the nearest ($d \simeq 140$ pc) sites of ongoing star formation, in which objects in several different stages of the process are clearly visible, from deeply embedded, actively accreting (proto-)stars to the final stages of star formation represented by the Weak-Line T Tau stars with no remaining circumstellar material. In this paper we are concerned with the jet associated with the IRS5 source embedded in the L1551 cloud and its associated outflow.

L1551 IRS5 is a deeply embedded proto-stellar binary system in the L1551 cloud, and it is effectively invisible at optical wavelengths as it is hidden behind some $\simeq$ 150 mag of visual extinction (White et al. 2000) which most likely originates in the circumstellar accretion disk. The two Class 0/1 stars have a total luminosity of $\approx 30\,L_\odot$, and appear to be (jointly?) powering at least two observable outflows, a large (several arcmin) bipolar molecular outflow and a much smaller (with a length of $\approx$ 10 arcsec) denser two-component jet (Fridlund & Liseau 1998), consisting of material at temperatures of $T \simeq 10^4$ K, thus visible in the emission lines of e.g. Hα. The jet moves at transverse velocity of 200–400 $\mathrm{km\,s^{-1}}$ (Fridlund & Liseau 1994) and appears to end in a shock against the ambient medium (a "working surface")

3. XMM-Newton observations

The X-ray observations presented here were obtained with the XMM-Newton observatory. A deep (50 ks exposure) of the star-forming region of the L1551 cloud was obtained starting on Sep. 9 2000 at 19:10 UTC. All three EPIC cameras were active at the time of the observation, in full-frame mode, with the "medium" filters. Here we present the data obtained with the EPIC-PN camera.

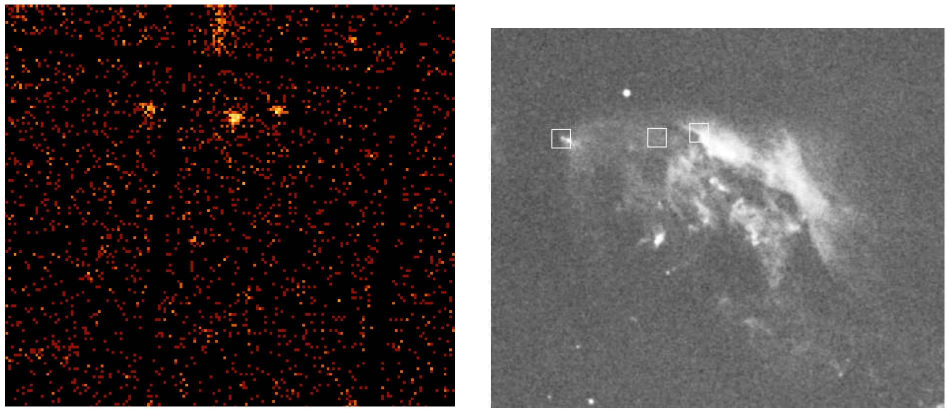

Figure 1. The left panel shows the region of L1551 in X-rays, as seen in the XMM EPIC-PN camera, while the right panel shows the same region as seen in a 300 s R-band CCD image obtained at the Nordic Optical Telescope. The two images are not exactly on the same scale; the position of the three X-ray sources visible in the left panel is indicated on the R-band image by the three white squares. The leftmost X-ray point source is the one associated with L1551 IRS5, while the central and rightmost point sources are two background sources unrelated with the jet.

An X-ray source (the leftmost of the three sources in Fig. 1) is clearly visible at the position of the IRS5 jet, with two additional sources visible in the region of the molecular outflow. For each of these sources source photons have been extracted from a circular region of 45 arcsec diameter, while background photons have been extracted from a region on the same CCD chip and at the same off-axis angle as for the source region. The spectral analysis has been performed using the XSPEC package, after rebinning the source spectra to a minimum of 20 source counts per (variable width) bin. The background-subtracted count rate for the X-ray source associated with IRS5 is 8.4×10^{-4} cts s^{-1} in the EPIC PN camera, so that 42 source cts are collected the $\simeq 50$ ks exposure, allowing only a limited amount of spectral information to be derived for the source. The resulting spectrum (shown in Fig. 2) is soft, and can be reasonably described with a moderately absorbed thermal spectrum. The best-fit column density ($1.4 \pm 0.4 \times 10^{22}$ cm^{-2}) corresponds to an extinction of $A_V = 7.3 \pm 2.1$ mag. The best-fit temperature is $T = 0.5 \pm 0.3 \times 10^6$ K.

The full width at half energy (FWHE) of the XMM point-spread function (PSF) for EPIC PN camera is ≈ 15 arcsec, significantly larger than the size of the jets (whose visible length is ≈ 10 arcsec). Thus, it is not possible to locate the precise site of the X-ray emission within the jet structure.

The two additional X-ray sources visible in Fig. 1 have spectra and absorbing column densities compatible with their being background active galactic nuclei shining through the molecular outflow, and are thus most likely unrelated with IRS5 and its jet/outflow structure.

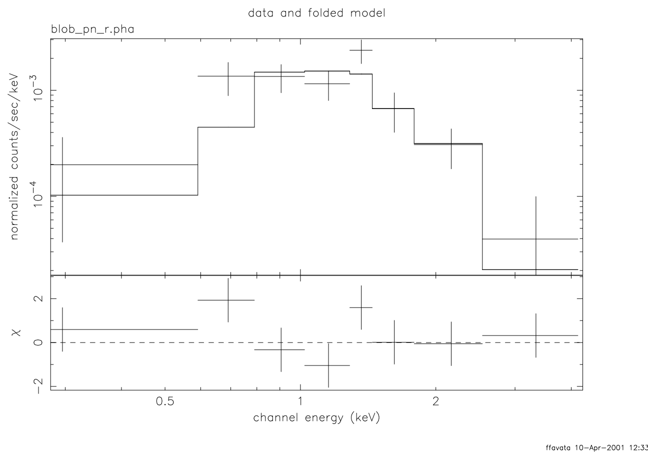

Figure 2. The observed, background-subtracted EPIC PN X-ray spectrum of the X-ray source associated with the L1551 IRS5 jet. The best-fit thermal spectrum is also shown.

4. Discussion

The IRS5 jet has a number of shocks along it, and it is observed to end in a "working surface" against the ambient medium at ≈ 10 arcsec from the presumed location of the source powering it. The absorbing column density toward the jet is estimated at 4–6 mag, a value compatible with the X-ray measured column density, making the association between the X-ray emission and the jet highly plausible. Since the IRS5 proto-stellar system is hidden behind a very thick layer of absorbing material, corresponding to $A_V \gtrsim 150$ mag, it can be excluded that the X-ray photons – given the small absorbing column density and the lack of high-energy photons in the spectrum – emanate from (or close to) the photosphere/chromosphere of the proto-stars powering the jet. We therefore draw the conclusion that this source is the result of thermal emission in the shocks whose recombination light is seen along the jet in the visual wavelength regime.

As discussed in detail by Favata et al. (2001), the fluid velocity in the shock is ≈ 270 km s^{-1}, with an inclination, i, of ≈ 45 deg. The immediate post-shock temperature can then be estimated at $T_{\rm ps} \simeq 0.67$ MK, fully compatible with the observed X-ray temperature of 0.5 ± 0.3 MK. Thus, the observed X-ray emission is likely to be due to material heated at the interface shock (the working surface) between the jet and the ambient medium medium, or possibly in shocks along the cavity excavated by the jet. The X-ray luminosity of the emission associated with the jets is $L_{\rm X} \simeq 3 \times 10^{29}$ erg s^{-1} (assuming a distance of 140 pc for the L1551 complex).

While the jet's X-ray luminosity is at the low end of the X-ray luminosity distribution of typical PMS stellar X-ray sources, the location of the emitting source some 10 AU *above* the star and thus the disk may result in a relevant effect of the jet's X-ray emission on the conditions of the disk even in the presence of a higher stellar X-ray luminosity. The X-ray emission coming from the jet's shock will illuminate the disk from above (and below), and can thus change the

ionization of the disk's material at large distances from the proto-star, in regions which are normally (unless the disk is very strongly flared) shielded from the influence of the stellar X-ray emission.

4.1. Energetics

The mass of the jet (see Favata et al. 2001 for the details) can be estimated at 1–2 $\times 10^{-6}$ $M_{\odot}$, which, with a shock velocity of ≈ 200 km s^{-1}, results in a mechanical luminosity of the jet of 10^{41}–10^{42} erg s^{-1}, so that a very low conversion efficiency between mechanical and radiant luminosity is sufficient to justify the observed X-ray luminosity from the shock. The Hα luminosity is $\approx 4.7 \times 10^{28}$ erg s^{-1}, comparable with the X-ray luminosity derived here.

5. Conclusions

While the energetic nature of the collimated jets observed to be originating from proto-stellar sources has been evident for some time, no high-energy photons have up to now been observed from these phenomena. Here we report the first convincing evidence of X-ray emission from the proto-stellar jet associated with the IRS5 proto-star(s) in the L1551 cloud. The X-ray source and the proto-star and related jets are positionally coincident, and the small absorbing column density observed for the X-ray spectrum ($\simeq 7$ mag, fully compatible with the absorbing column density observed towards the jet) allow us to exclude that the X-ray emission is associated with the proto-stellar sources (which are hidden behind ≈ 150 mag of obscuration). The size of the jets (≈ 10 arcsec) originating at L1551 IRS5 is smaller in angular extent than the XMM EPIC PSF (≈ 15 arcsec), so that no inference is possible on spatial grounds about the possible detailed location of the origin of the X-ray emission.

The emission from the IRS5 jet is compatible with being caused by thermal emission from a plasma heated to a moderate temperature ($T \simeq 0.5$ MK). This is equivalent to the shock temperature that is expected at the interface ("working surface") between the jet and the surrounding circumstellar medium, on the basis of the observed jet velocity.

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